1. **Solid State Physics Review**

Pure or "intrinsic" Silicon:

- above absolute zero: small number of free e⁻'s for conduction
- \( n_i \approx \) density of these free e⁻'s
- \( N_i \approx "\text{intrinsic carrier density}" \)
- \( [n_i] = \text{cm}^{-3} \)

\[ n_i^2 = B T^3 e^{-E_g/kT} \]

\( n_i^2 = \text{cm}^{-6} \)

\( E_g = \text{bandgap energy, } [E_g] = \text{eV} \)

- min energy needed to break a covalent bond in the semiconductor crystal, freeing e⁻'s

\( E_g \) is a material property

<table>
<thead>
<tr>
<th>material</th>
<th>( E_g ) (eV)</th>
<th>( a )</th>
<th>color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>1.106</td>
<td>IR</td>
</tr>
<tr>
<td>Ge</td>
<td>0.66</td>
<td>1.877</td>
<td>IR</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>0.8725</td>
<td>IR near visible</td>
</tr>
</tbody>
</table>

\( K = \text{Boltzmann's constant } = 8.62 \times 10^{-5} \text{ eV/K} \)

\( T = \text{absolute temperature in K} \)

\( B = \text{material-dependent parameter in K}^{-3} \cdot \text{cm}^{-6} \)

<table>
<thead>
<tr>
<th>material</th>
<th>( B ) (K(^{-3}) \cdot \text{cm}^{-6})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>( 1.08 \times 10^{21} )</td>
</tr>
<tr>
<td>Ge</td>
<td>( 2.31 \times 10^{20} )</td>
</tr>
<tr>
<td>GaAs</td>
<td>( 1.27 \times 10^{29} )</td>
</tr>
</tbody>
</table>
Figure 2.1  Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length $l = 0.543$ nm. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis.

Source: (a) and (b) Adapted from Electrons and Holes in Semiconductors by William Shockley, © 1950 by Litton Educational Publishing. (c) Adapted from The Architecture of Molecules by Linus Pauling © 1964 by W. H. Freeman and Company, used with permission.
$n \equiv$ density of conduction (or free) electrons

$[n] = \text{e}^-/\text{cm}^3$

For intrinsic Si: $n_i = n$

For single crystal (monocrystalline) Si: 4 covalently bonded atoms

Energy $\geq E_0$ results in the creation of an electron-hole pair
- Electrons can move anywhere
- Holes can only move about the crystal lattice

Electrons and holes are charge carriers

\[
\begin{align*}
\downarrow & \quad \downarrow \\
-\text{e}^- & \quad +\text{e}^- \\
\Rightarrow & \\
\text{g} & = 1.62 \times 10^{-19} \text{C}
\end{align*}
\]

$p \equiv$ hole density, $[p] = \text{holes/cm}^3$

For intrinsic Si: $n_i = n = p$

$n_i^2 = pn \rightarrow$ whenever there is thermal equilibrium w/o external stimulus (voltage, current, light)

Electrical resistivity $\equiv \rho = \frac{1}{\sigma}, \sigma \equiv$ conductivity
a. Drift Currents

charged particles move (drift) in response to an applied electric field - results in a drift current, \( j \)

\[ j = Qv, \quad [j] = A/cm^2 \]

\( Q \) = charge density, \([Q] = C/cm^3\)

\( v \) = charge velocity in the electric field - also called "carrier drift velocity"

\([v] = \text{cm/s}\)

positive charges move in direction of the E field

negative charges move in opposite direction of the E field

For low electric fields : \( v \propto E \) - of interest to this class

\[ \vec{v}_n = -\mu_n \vec{E} \]

\[ \vec{v}_p = \mu_p \vec{E} \]

where \( \vec{v}_n \) = velocity of electrons

\( \vec{v}_p \) = velocity of holes

\( \mu_n \) = electron mobility, 1350 cm²/V for intrinsic Si;

\( \mu_p \) = hole mobility, 500 cm²/V for intrinsic Si;

Notice \( \mu_n > \mu_p \): e⁻'s can move freely through crystal while holes can only move about the crystal through the covalent bond structure
Electron and hole drift current densities, $j_n^{\text{drift}}$ and $j_p^{\text{drift}}$

$[j_n^{\text{drift}}, j_p^{\text{drift}}] = \text{A/cm}^2$

1-D vectorless equation versions:

$j_n^{\text{drift}} = q_n v_n = (q_n)(-\mu_n E) = q_n \mu_n E$

$j_p^{\text{drift}} = q_p v_p = (+q_p)(+\mu_p E) = q_p \mu_p E$

Total drift current density $\equiv j_T^{\text{drift}}$

$j_T^{\text{drift}} = j_n^{\text{drift}} + j_p^{\text{drift}} = q_n(\mu_n + \mu_p)E = \sigma E$

$\sigma = \text{electrical conductivity} = q_n(\mu_n + \mu_p), \quad \sigma = \text{(S/cm)}$

$\rho = \frac{1}{\sigma} \equiv \text{resistivity}$

Note:

$\rho = \frac{E}{j_T^{\text{drift}}} \quad \Rightarrow \quad \rho \cdot \text{cm} = \frac{V\text{cm}}{\text{A/cm}^2}$

$\downarrow$

$R = \frac{V}{I} \rightarrow \text{Ohm's law}$

3. Doping

Doping is the process of adding impurities to the intrinsic semiconductor material.

**Donor Impurities** - one extra $e^-$ in outer shell: donate $e^-$'s

**Acceptor Impurities** - one less $e^-$ in outer shell: donate holes

Si: a Column IV element: 4 valence $e^-$'s in outer shell